National Aeronautics and
Space Administration
Goddard Space Flight Center
Greenbelt, MD 20771

Reply to Attn of: 302

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TO: 924/Dr. Robert Afzal
SSAI(924)/Dr. Joe Dallas

FROM: 302/ Systems Safety and Reliability Office

SUBJECT: Updated Laser Diode Bar Life Test Failure Data Analyses

Abstract

Updated analyses on the SDL laser diode bars were performed using data current to when the life tests were terminated. Failure data fit two distributions: an initial exponential (constant failure rate) distribution to 4 billion shots and a subsequent "wear-out" distribution beginning after about 4.7 billion shots. A calculated MTTF for the exponential distribution (random failures) was 4.4 billion shots, which corresponded well with Weibull-predicted 50% failures at about 5 billion shots. Ninety per cent confidence bounds on the calculated MTTF were 2.4 and 11.0 billion shots (Chi-squared calculation on the exponential distribution), compared to 2.5 and 6 billion shots for the Weibull plot. These data did not account for power derating nor repetition-rate acceleration. Thus they conservatively predict that GLAS laser diode bars should reach or exceed the goal of 1.5 billion shots per laser assembly, assuming the flight bars exhibit no infant mortality failures.

Introduction

Data from the Geoscience Laser Altimetry System (GLAS) laser diode bar life tests previously had been analyzed while the Code 924 life tests were still being run [1]. For this 1998 analysis, the life test bars had undergone approximately three billion shots. That data was used to predict laser assembly failure rates as part of the total instrument reliability analysis. Life test details were presented in Ref. [2].

Life tests were continued until late spring 1998, when they were terminated. By then, most bars had accumulated approximately 4.7 billion shots. This revised data was analyzed to update the laser diode bar failure rates.

Analyses

Detailed life test data was furnished by Dr. Afzal for each of nine SDL 3255 100 W laser diode bars. These data were analyzed to determine when the light output of each bar had decreased to 80 per cent of its original (zero-time) light output. This failure criterion (20 per cent degradation) was the same as used in the previous analyses [1,2].

Since the data showed some "noise" (scatter) between succeeding measurements, the time (in numbers of shots) when each bar had decayed to 80 per cent was determined by plotting light output decay versus time. The 80 per cent point was defined as six or more points in a run of ten points being below the "80 per cent line." The 80 per cent line was calculated as 0.8 times the zero time light output. This method was used for bars U421, U920, X310, X311, X346 and X387. This more accurate method of determining times to failure (TTFs) resulted in some of the failure times changing from the previous analysis. The revised failure times are U421 5.16 billion shots (previous TTF was 5.0 billion shots), U920 1.14 (1.0), X310 3.59 (3.0, not failed), X311 1.504 (1.5), X346 0.305 (0.33), and X387 2.54 (2.47) billions of shots. Note that bar X310 now showed a failure at 3.59 billion shots, whereas previous data showed no failure at 3.0 billion shots. These revised data are shown in Table I, below.

Bar U350 was used in a different test (i.e., this bar was not continuously monitored) so only zero and end time data were available. A linear extrapolation between the start and end light outputs was used to estimate the number of shots to failure (TTF). The calculated TTF was 6.56 billion shots, compared to 7 billion used in the previous analysis.

Bars X367 and X437 operated without failure; they were time-terminated at 4.71 billion shots. Bars X389, X390, X391 and X392 had been run in a separate life test by the manufacturer [2]; all operated without failure to between 2.3 and 3.8 billion shots. Since this life test was separate from the Code 924 tests, these four bars accrued no additional operating time.

Table I. SDL 3225 Laser Diode Bar Life Test Data

Diode Bar S/N	# bars/ package	[1]Optical Power W	# shots $x10^9$	F/S [4]	Old # shots $x10^9$	Old F/S	Power Derate	Temp °C
X346	1	61.0	0.3045	F	0.33	F	25%	20
U920	1	80.0	1.1384	F	1.0	F	0	24
X311	1	79.9	1.5045	F	1.5	F	0	20
X392*	6	90.6 [2]	2.3	S	2.3	S	0	20
X387	1	70.4	2.5383	F	2.47	F	12	30
X389*	6	92.7	2.8	S	2.8	S	20	20
X310	1	80.0	3.5885	F	3.0	S	0	30
X390*	6	96.5	3.8	S	3.8	S	40	20
X391*	6	97.8	3.8	S	3.8	S	40	20
X367	1	50.3	4.7072	S	3.0	S	40	20
X437	1	50.3	4.7072	S	3.0	S	40	30
U421	3	80.0	5.1599	F	5.0	F	0	25
U350	1	70.9 [3]	6.5613	F	7.0	F	10	24

[1] The measured optical power corresponding to the "# shots x 10^9" column.
[2] For the manufacturer-run life tests (*) on six-bar packages, "Optical Power" represents 100 less the % degradation from the zero-time light output.
[3] For U350, 70.9 W power measured after 7 billion shots; TTF calculated as an 80% linear decay.
[4] "F/S" column indicates failure or suspension (no failure).

Data on all thirteen bars were analyzed using a Weibull analysis [3] to determine the failure distribution(s); see the Weibull plot in Figure 1, below. The data showed a good fit to a "mixed Weibull," i.e., there were two failure distributions. The initial distribution contained the first nine points and fit an exponential (random) failure distribution having $\beta = 1.0$ and $\eta = 4.9$. The second distribution of the last four points had $\beta = 7.6$ and $\eta = 5.5$. The data fit with a correlation coefficient of 0.96. The dashed lines represent upper and lower 90% confidence intervals.

Since the first nine points fit an exponential (constant failure rate) distribution, a mean time to failure (MTTF) was computed using a Chi-squared calculation for time-terminated tests. It was 4.35 billion shots with a 90% confidence interval of 2.35 (lower) and 11.05 (upper) billion shots.

An attempt was made to quantify the power derating and temperature effects on laser diode power output. The Code 924 data were reviewed to determine each diode's power output after 1.5 billion shots; these were normalized to the original (t = 0) power outputs. (The manufacturer's life test data were not included since interim data were not available.) These power outputs are shown as Table II.

Table II. Normalized Laser Diode Power Outputs at 1.5 Billion Shots

Diode Bar S/N	Temp °C	Power Derating %	Normalized Optical Power, %
X311	20	0	80.2
X346	20	25	71.1
X367	20	40	87.5
U920	24	0	78.0 [1]
U421	25	0	94.0 [1]
U350	24	10	95.8 [1]
X310	30	0	87.0
X387	30	12	88.3
X437	30	40	92.6

[1] Estimate based on linear regression; interim data not available or incomplete.

The above data also are in Figure 2, below. There is a slight indication of an increase in normalized output at 1.5 billion shots with power derating. The data were too limited to draw any rigorous statistical inference; the non-orthogonal data arrangement precluded performing an analysis of variance.

Discussion

When performing failure data analyses, one ideally would differentiate devices by their life test stresses and conditions. Because of the dearth of test bars all data were combined and assumed to bc from the same population. This is not inappropriate since all bars were manufactured as one lot on the same production line. Including the manufacturer's life test (bars X389, X390, X391, X392) added four additional data points for which no failures occurred. Excluding these four data simply moved the Weibull plot slightly to the left; the initial distribution was still exponential ($\beta = 1.01$ and $\eta = 3.8$) followed by the same increasing failure rate distribution ("wearout").

Figure 1 predicts that the MTTF (mean time to failure) for the GLAS laser diode bars to be 4.5 billion shots, with 90% confidence bounds of 2.5 and 6.0 billion shots. To meet the mission goal of 1.5 billion shots the data predict a minimum (at 90% confidence) failure probability of 6% and a maximum (at 90% confidence) of 38%. The "wearout" failure mode is predicted to begin at about 5 billion shots, with a 33 to 78% failure probability (again with 90% confidence) at this time.

These predictions account for neither an accelerated repetition-rate (GLAS life test diode bars had a duty cycle of about 200 Hz versus a flight duty cycle of 40 Hz) nor power derating (GLAS flight diode bars will be derated to between 60 and 80%, depending on application). Thus these life test data represent a *conservative* estimate of GLAS laser diode bar on-orbit life. Implicit in these predictions is no infant mortals (failures) occurring in the flight devices.

The confidence bounds between the Weibull analysis (2.5 and 6.0 billion shots) and the Chi-squared calculation (2.4 and 11.0 billion shots) differed because the Weibull data included all 13 data points and the Chi-squared calculations used only the first 9 points of the initial, exponential distribution. Nonetheless, the agreement between the two methods reinforces one's confidence in the statistical predictions.

Conclusions and Recommendations

1. Weibull analysis of Code 924 laser diode bar life tests showed two "mixed" failure distributions. The initial failure distribution (first nine points) fit an exponential (constant failure rate) distribution having Weibull parameters of $\beta = 1.00$ and $\eta = 4.92$, indicative of randomly occurring failures. The second distribution (last four points) had Weibull parameters of $\beta = 7.6$ and $\eta = 5.5$, indicating a wearout, or increasing failure rate, has begun. Both β and η are in units of billions of shots.
2. The predicted mean-time-to-failure (MTTF) for the Weibull data was 4.5 billion shots, with a 90% confidence interval of 2.5 and 6.0 billion shots. The probability of failure at 1.5 billion shots is about 19% (with 90% confidence bounds of 6 and 38%).
3. A MTTF calculated from the initial nine points is 4.35 billion shots which compares satisfactorily with the Weibull MTTF.
4. The predicted failure rates do not account for duty cycle or power derating; they are thus a conservative prediction of GLAS laser flight performance.
5. No estimates were possible on temperature and power derating from the available data. Any subsequent laser diode life tests should be designed using a design-of-experiments approach to facilitate deriving such effects.

Acknowledgements:

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References:

1. W. Thomas, "Weibull Analysis of Laser Diode Bar Life Tests," NASA GSFC Memorandum to R. Afzal and J. Dallas, June 17, 1998, 3 pp.
2. M. A. Stephen, M. A. Krainak and J. L. Dallas, "Quasi-CW Laser Diode Bar Life Tests," *29th Annual Boulder Damage Symposium Proceedings, Laser-Induced Damage in Optical Materials: 1977*, 6-8 October 1997, Boulder, Colorado, Proceedings of SPIE - The International Society for Optical Engineering, Volume 3244, pp. 598-603.
3. *Weibull ++* software, ReliaSoft Corporation, Tucson, Arizona.

Walter Thomas

Walter Thomas
Reliability Engineering

Cc: R. Follas/924
Dr. J. Abshire/924
Dr. E. Ketchum/924
J. Garvin/302
M. A. Stephen/554

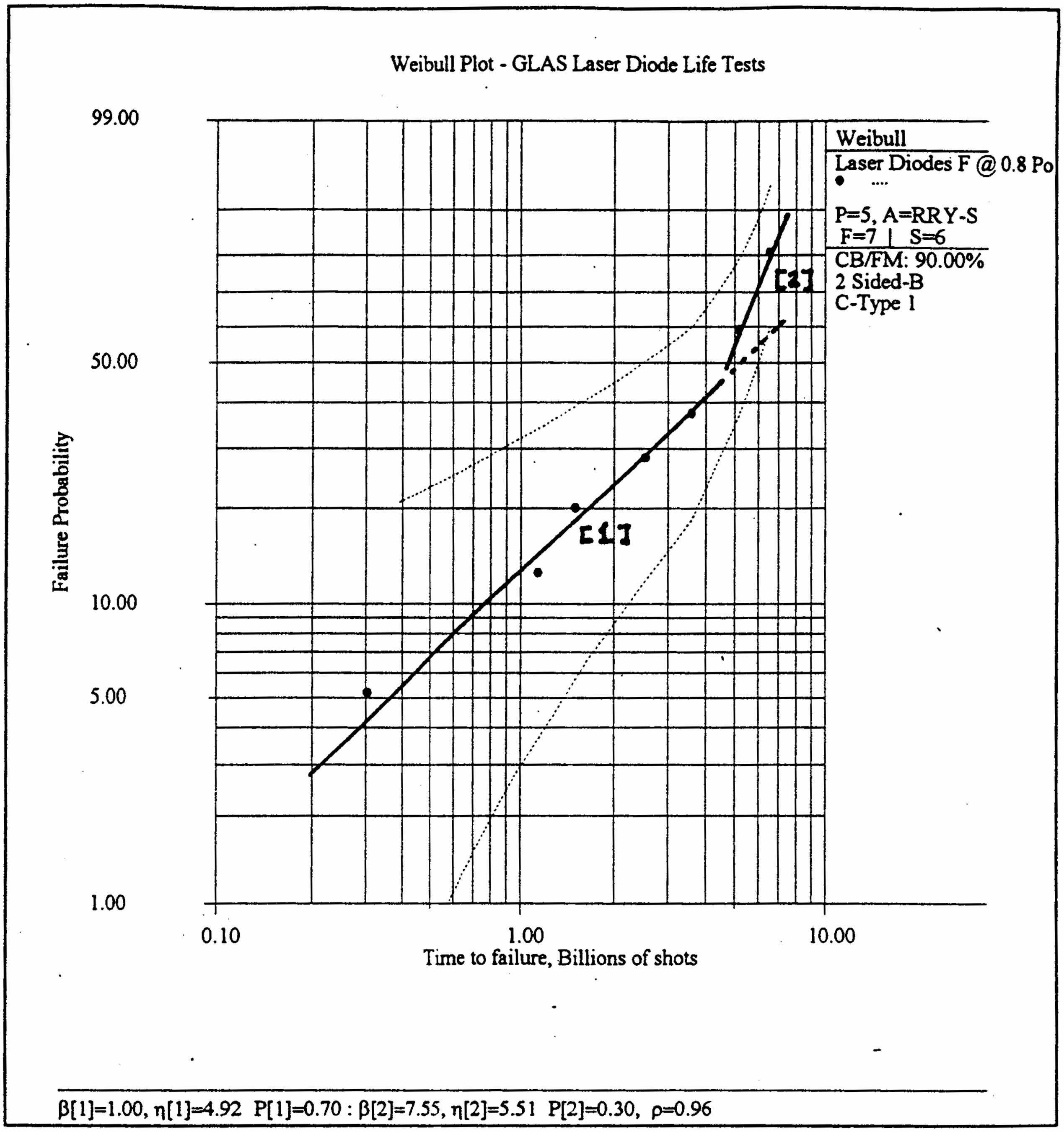

Figure 1. Weibull plot of Code 924 laser diode bar life tests, using 0.8 Po(0) as the failure criterion.

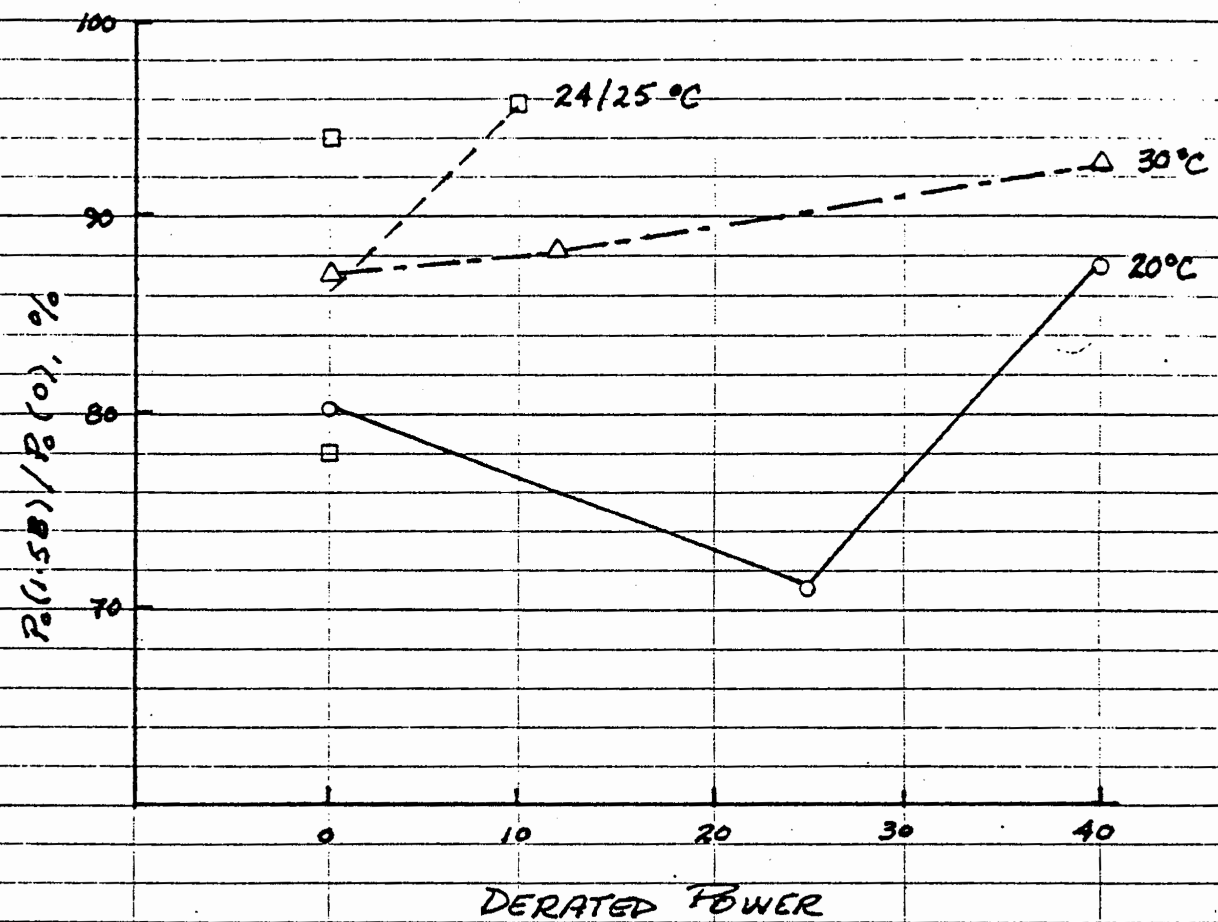

Figure 2. Normalized light output at 1.5 billion shots for Code 924 laser diode bar life tests.

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